

Corona Treatment: An Overview

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ABSTRACT

With the advent of readily available nonpaper substrates (plastics and foils) in the mid-to-late 1950's, the requirement for a reliable production speed surface treatment process became apparent. Several different technologies have been tried, but one, corona treatment, has become, by far, the primary surface treatment technology used across the Extrusion and Converting Industries. We will touch on these various technologies, technically describe the need for surface treatment and how it is measured, trace the development of corona treatment as the leading surface treatment method, and detail the current state-of-the-art in equipment, control parameters and applications.

Introduction

Necessity of Surface Treatment

Generally, plastics have chemically inert and nonporous surfaces with low surface tensions causing them to be nonreceptive to bonding with substrates, printing inks, coatings, and adhesives. Polyethylene and polypropylene are the lowest in surface energy of the various plastics and are the two materials most often subjected to surface treatment to improve their bonding characteristics (1) (2) (3).

Surface treatment, however, is not limited to these two materials and can be used to improve the bonding ability of virtually all plastic materials as well as some nonplastic materials. The two nonplastic materials most often subjected to surface treatment are foil and paper. All substrates, plastics, films, paper and foils provide a better bonding surface when they are treated at the time they are produced. This application is referred to as post-treatment and is used to enhance adhesion to the surface of other converting processes such as printing, adhesive lamination, etc.

Methods of Improving Surface Tension

The four methods by which surface treatment is accomplished are as follows (4):

1. Corona discharge (5) (6) (7).
2. Etching with acid or plasma.
3. Flame treatment (8).
4. Priming (9).

Priming is still frequently used alone or in combination with corona discharge treating. Another method used almost exclusively in extrusion coating is ozone treatment.

Flame and etching are frequently used for molded or blow-molded parts. Flame treatment of film and sheet had been almost completely supplanted by corona discharge surface treaters. However, flame treating has seen a comeback recently, especially on paperboard or milk carton stock.

Flame Treatment

Four variables control the optimum treatment conditions of a flame, they are:

1. Air-to-Gas Ratio
2. BTU (kj) Output of the Burner
3. Distance of Surface from Flame Tips
4. Dwell Time of Surface in Oxidizing Zone

Figure 1 is an overall flow diagram of the various components of a flame treatment system. A high-volume, low pressure centrifugal air blower moves a column of air through a venturi mixer. The venturi section is adapted with a needle valve to pull gas according to demand from a pressure-regulated gas line.

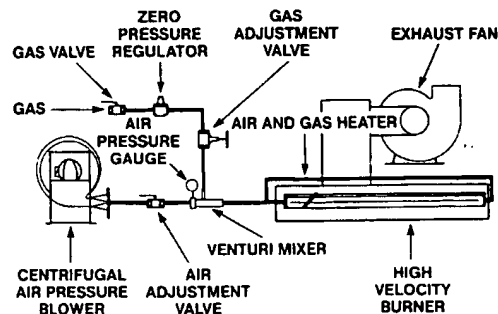


Figure 1. Flow Diagram of the Flame Treatment System.

The resulting air/gas mixture, with a 5 to 15% excess of air, is conveyed to the burner face and ignited. The flame's oxidizing zone, which is optimum at 3/8" to 1/2" from the flame tip, impacts on the substrate surface and the excess oxygen activated by the high temperatures combines with carbon molecules to form the polar groupings generally associated with an oxidized surface. The treated surface is approximately one molecular layer thick.

The waste heat from this process can be reclaimed by various energy interchange methods and can be returned as usable heat for drying or even for building heat. Some plants with proper insulation have been completely heated during the winter months by such recycling processes.

Figure 2 shows a cross section of a flame treater burner which features a wide and clean-ported equalizing chamber with relatively large precision orifices drilled along the exit area. The lean gas mixture is combusted in a flame guard zone which prepares the gaseous envelope for impact with the substrate. This flame guard also protects the burner orifice from blockage by pieces of paper or plastic scrap charring and melting, thus sustaining the flame characteristics in a more pristine state for a longer period of time (8).

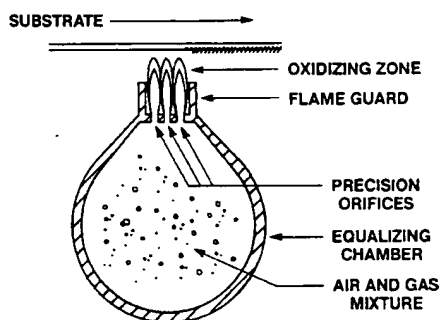


Figure 2. Flame Treater Burner.

This system provides the additional control necessary to overcome the problems inherent in earlier flame treating systems, such as inconsistent treatment levels and slow response during a line shutdown, while maintaining the required treatment levels.

Flame analyzers now compensate for changes in ambient temperature, gas composition and humidity to maintain a proper oxidizing flame. Burner capacity or firing rate is automatically adjusted to changes in line speed.

Measuring Surface Energy

The object of surface treating is to improve the wettability of the surface, thereby improving the ability to bond to solvents, adhesives, coatings, and extrusion coating. In order for a surface to be properly wet by a liquid, the surface energy of the plastic must be higher than the surface tension of the liquid. Surface energy is measured in dynes per centimeter. Ideally, the surface energy of the plastic should be 7 to 10 dynes/cm higher than the surface tension of the solvent or liquid. For example, a printing ink having a surface tension of 30 dynes/cm would not

adequately wet or bond to a material having a surface energy less than 37 to 40 dynes/cm (see Figure 3).

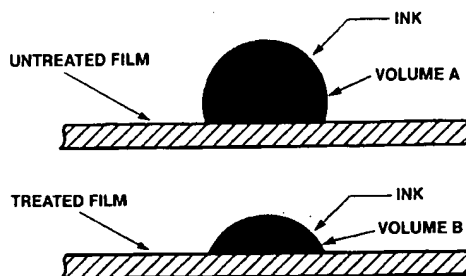


Figure 3. Ink Drop on Film Surface.

One method for measuring surface energy known as the Wetting Tension Test (ASTM D-2578) was established a number of years ago (10). Surface energy testing is frequently done on post-treatment surfaces prior to follow-on converting processes. With this test, a series of mixed liquids with gradually increasing surface tensions are applied to a treated substrate surface until one is found that just wets the surface. The surface energy of the plastic is approximately equal to the surface tension of that particular mixture. Test solutions are available from various manufacturers of corona treating equipment. Table I details the ratio of Formamide and Cellosolve™ for various surface tensions. Cellosolve™ is a registered trademark of Union Carbide for ethylene glycol monoethylether.

The wetting tension test method is by far the most prevalent measurement used to determine treatment level of post-treated surfaces. Several other methods are in limited use and are detailed in Table 2.

Of these methods, one of the most accurate when properly performed is contact angle measurement. To establish a new equilibrium between substrate surface characteristics, coating material characteristics, and production processes and methods, an accurate method of testing is required. Some years ago, Dr. William A. Zisman, while working with equations developed by Thomas Young, developed the mathematical and practical underpinnings of testing surface tension using accurate contact angle measurement (11). Zisman's work cannot be fully discussed here, but Figures 4, 5, and 6 provide simple demonstrations of the theory. Much of the experimental work done over the past few years has ignored wetting tension solutions as a method of surface tension measurement in favor of contact angle measurement (6) (7) (12) (13) (14). Several companies are currently marketing devices for accurate contact measurement.

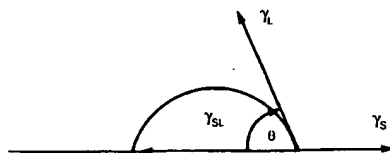


Figure 4. Substrate Surface Tension > Liquid Surface Tension.

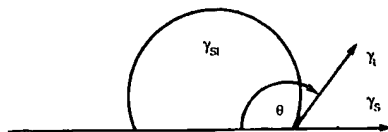


Figure 5. Substrate Surface Tension < Liquid Surface Tension.

$$\gamma_L \cos \theta + \gamma_{SL} = \gamma_S - \pi_v$$

Where: γ_L , γ_S , and γ_{SL} are the free energies of the liquid and solid against their saturated vapor and of the interface between liquid and solid respectively, π_v is the equilibrium pressure of the absorbed vapor of the liquid on the solid, and θ is the equilibrium contact angle.

Figure 6. Surface Tension Formula.

ASTM Test Methods: Dyne Solution Test Methods

Over the years there have been many methods of measuring the wettability or treatment level of the web surface. All of these methods require a subjective interpretation by laboratory personnel. In many converting establishments, a test method has been chosen to become a shop preference. Probably the most accepted method is the wetting tension test using cotton swabs and ASTM Standard Concentration Solutions of formamide and Cellosolve™. This method, although providing an established procedure for determining surface energy, does present several problems in reliability and consistency of results. Problem areas should be addressed in the following ways:

1. Care must be taken to limit evaporation of solutions. Evaporation changes concentrations and, thereby, changes dyne level values.
2. Cotton swabs have been found to have widely different effects on dyne level indications because various manufacturers of swabs use different binders to hold the cotton to the end of the stick.
3. Testing a cotton swab in different dyne solutions contaminates both the results of the tests and the bottle of the solution.
4. Although the mixtures of ethyl Cellosolve™ and formamide used in this method are relatively stable, exposure to temperature or humidity extremes should be avoided.
5. Laboratory personnel using cotton swabs have a tendency to vary the amount of liquid picked up by the cotton swab, thus varying the results of the test. Also, the method of rubbing the liquid onto the polyolefin surface with a cotton tipped applicator varies from person to person. This rubbing force also tends to give erratic dyne level results. It is important to maintain an even coating thickness of wetting tension solution which will result in uniform test results.

Cotton Swab Method

The wetting tension test using cotton swabs and the dyne level solutions will measure the surface tension of polyolefin film surfaces in contact with drops of a specific solution in the presence of air. Solutions are applied to the surface of the film until a solution is found that just wets the surface of the film.

A reading of the liquid behavior should be taken in the center of the liquid. Severe peripheral shrinkage of the liquid may be caused by placing too much liquid on the film surface.

The step-by-step test procedure is as follows:

1. Wet the tip of the applicator with test solution from a calibrated dyne level solution stock container. A minimum amount of solution should be used because an excess can distort the reading.
2. Spread the test solution lightly over approximately one square inch of the test material.
3. Note the time it takes for the liquid to break into droplets. If the liquid does not break into droplets within two seconds, repeat the test with a surface tension solution of the next higher rating. If the liquid breaks into droplets in less than two seconds, repeat the test with a surface tension solution of the next lower reading. Be sure to use a clean cotton applicator each time the test is repeated to avoid contaminating the solution and distorting the test results.
4. Repeat steps one through three until the solution holds for exactly two seconds before breaking into droplets. The surface tension in dynes/cm of the test solution is the surface energy of the material.

This testing procedure has been a standard of the industry for many years, but the results of the testing procedure have been somewhat inconsistent and varied by laboratory personnel.

Drawdown Test Method

An alternative method (the results of which are generally easier for lab personnel to evaluate) is to use a drawdown rod rather than a cotton-tip applicator to establish a uniform thickness of wetting tension solution on the polyolefin sample (see Figure 7).

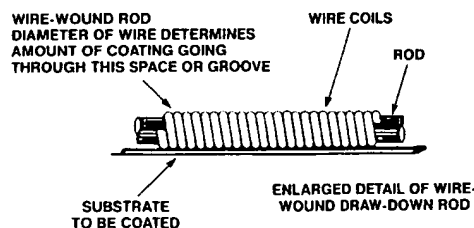


Figure 7. Enlarged Detail of Wire-Wound Drawdown Rod.

The following is a step-by-step procedure for measuring wetting tension solution using the dyne solution drawdown technique:

1. The film to be tested is cut in samples that will fit on a clipboard. The sample is usually about 8 x 11 inches.
2. Select three dropper bottles of dyne solutions which bracket the desired treatment level. Typically, if a surface treatment specification is for 42 dynes/cm \pm 2 dynes/cm, one would select the following wetting tension solutions: 40 dynes/cm, 42 dynes/cm, and 44 dynes/cm.
3. Place a film sample on the drawdown clipboard and visually divide into three equal-sized columns-ms, from left to right, in the order of increasing dyne level. Place two to three drops of each dyne solution in the top center of each column.
4. Take a wound-wire metering rod and place it in contact with the film just above the row of dyne solution drops. With a smooth, continuous movement, draw the rod across the surface of the film so as to simultaneously draw down a thin continuous layer of each of the three dyne solutions (see Figure 8).

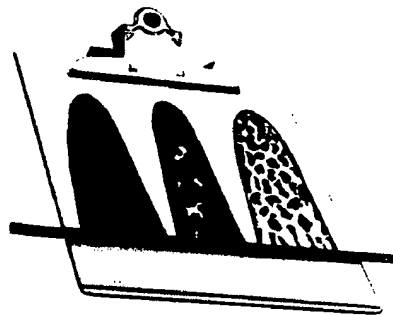


Figure 8. Drawdown of Three Dyne Solutions.

Interpreting the results of this test is very simple. If after a two-second interval, the three drawdowns appear as in Figure 8, the wetting energy of the film sample approximately equals the surface tension of the center column. The left column of the dyne solution remains continuous and unbroken after two seconds and therefore has a surface tension lower than the wetting energy of the treated film surface. The center column of the dyne solution just begins to break up into droplets after two seconds and therefore has a surface tension approximately equal to the wetting energy of the treated film surface. Finally, the right column of the dyne solution breaks up into droplets before two seconds and therefore has a surface tension higher than the wetting energy of the treated film surface.

If two or more columns remain unbroken after two seconds, then the choice of dyne solution strengths was too low, and the test should be repeated using higher dyne strengths. Of course, the opposite is true if two or more columns should break up into droplets before two seconds. It is necessary to thoroughly clean and dry the metering rod between each and every drawdown.

The various wetting tension solutions should be kept in stock bottles. The solutions actually used in the testing procedure should be kept in a small dropper bottle and capped to prevent evaporation. Although the wetting tension solutions are very stable, they must be kept in a relatively stable temperature environment. Electronic equipment is available for testing solutions and for accurately determining their surface tensions. Unfortunately, this equipment is very expensive and difficult for a converter's laboratory to justify. It is better to either manufacture or purchase wetting tension solutions from a reputable supplier.

The dye used in the wetting tension solution to make it visible on the polyolefin substrate should not be such as to affect the wetting tension of the test solution. Converters seem to prefer a very strongly dyed solution that is easily read by the laboratory technician, but a heavy concentration of dye may affect the integrity of the wetting tension solution.

Warnings & Cautions

When using wetting tension solutions, the converter should observe all safety precautions on the label of the wetting tension solution. Formamide may cause skin irritation and is particularly dangerous in direct contact with the eyes. Safety goggles should be worn when making up new test mixtures. Ethyl Cellosolve™ is a highly flammable solvent and precautions should be taken when using either the ethyl Cellosolve™ or the mixture of ethyl Cellosolve™ and formamide. Both ethyl Cellosolve™ and formamide are toxic and must be handled with due care, as indicated on the label. All tests must be performed in an adequately ventilated area.

According to the latest studies, solutions containing formamide and a combination of formamide and Cellosolve™ can have a teratogenic action. Female workers should therefore not be involved in the preparation of the wetting tension solutions.

Questions pertaining to the precautions appropriate for use of these fluids should be directed to the supplier. Users should obtain a material safety data sheet (MSDS) for each of the components of the wetting tension solutions. If the information is not available from the supplier, contact Union Carbide, the manufacturer of Cellosolve™, or a manufacturer of formamide, such as BASF Wyandotte Corp. An MSDS will give complete information regarding the precautions necessary for using these materials.

The wetting tension solution test, although not as objective as one might wish, will serve the converting industry until a more precise test is available. Attempts have been made to develop an in line surface tension testing method to close a loop with a computerized corona treating system, thus increasing the power output in conjunction with increased need for watt density. At this time, no such in-line testing system has been developed. The demand for such a testing method will undoubtedly cause the industry to continue its search. Table 3 lists various substrates along with their typical surface tensions.

Corona Treating

What Is Corona Treating?

A corona treating system is designed to increase the surface energy of plastic films, foils and paper in order to allow improved wettability and adhesion of inks, coatings and adhesives. As a result, the materials treated will demonstrate improved printing and coating quality, and stronger lamination strength.

The system consists of two major components:

1. the power supply, and
2. the treater station.

The power supply accepts standard 50/60 Hz utility electrical power and converts it into single phase, higher frequency (nominally 10 to 30 kHz) power that is supplied to the treater station.

The treater station applies this power to the surface of the material, through an air gap, via a pair of electrodes, one at high potential and the other, usually a roll which supports the material, at ground potential. Only the side of the material facing the high potential electrode should show an increase in surface tension.

A corona treating system in its simplest form can be portrayed as a capacitor (see Figure 9).

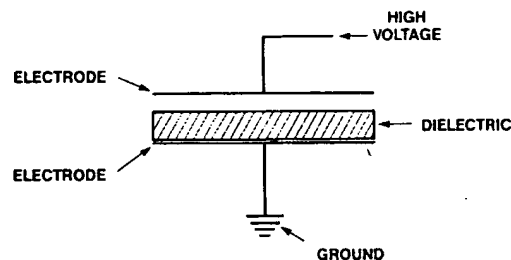


Figure 9. Capacitor.

Voltage is applied to the top plate which, in the case of a corona treating system, would be the electrode. The dielectric portion of the capacitor would be made up of some type of roll covering, air, and substrate in the corona treating system. The final component, or bottom plate, would take the form of an electrically grounded roll. In the corona treating system, the voltage buildup ionizes the air in the air gap, creating a corona which will increase the surface tension of the substrate passing over the electrically grounded roll.

History of Development

The configuration of the electrode has taken many forms. One of the earliest forms was a

simple wire stretched parallel to the ground roll which was covered by a dielectric such as polyester wrapping. The wire electrode (see Figure 10) accomplished its purpose, but provided such a narrow corona that the dwell time, the time which the substrate actually spent in the presence of corona, was exceedingly short. In addition, the power level that could be applied was extremely limited by the cross section capacity of the wire and its ability to dissipate heat generated during treatment. Ozone, which is always produced in the corona-filled air gap, had to be removed from the work environment.

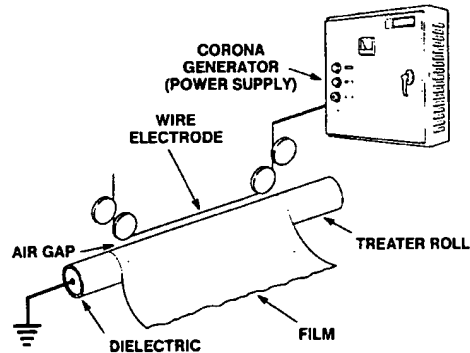


Figure 10: Wire Electrode

Another early form of electrode was a threaded rod which provided more dwell time, but because of the unevenness of the electrode surface, it had a tendency to create uneven treatment across the transverse of the substrate. Corona has a tendency to be more intensive at sharp points in the electrode (see Figure 11), causing higher treatment level where the threaded portion is closer to the substrate.

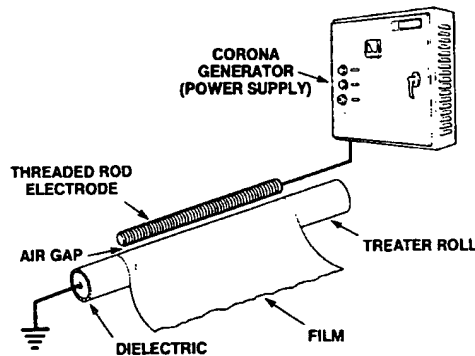


Figure 11. Threaded Rod Electrode.

Straight metal bar electrodes were also used, and are still being used today. The bar produces even treatment across the substrate but requires a new electrode to be cut to length to match the web width each time the web is changed. This is inconvenient for the operator and requires a storage system for various lengths of electrode (see Figure 12).

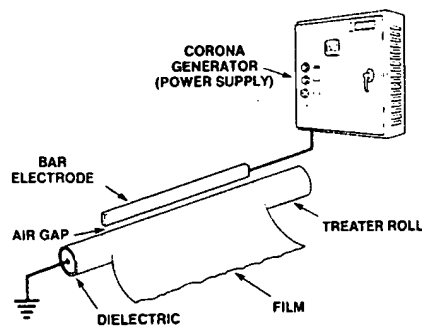


Figure 12. Bar Electrode.

In order to overcome the need to cut electrodes to length, bar electrodes were cut in segments and mounted on a rod so that when web width changed, segments could be moved away from the ground roll, thus matching the electrode length to the web width (see Figure 13). Many such electrodes are being used today. This configuration of electrodes has several advantages and disadvantages.

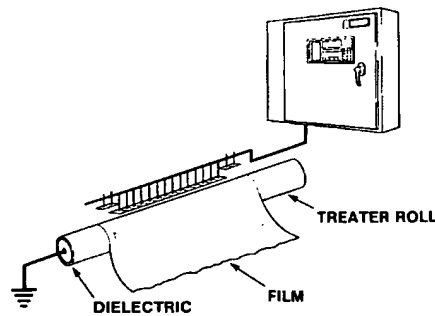


Figure 13. Segmented Metal Electrode.

When the segmented electrode was mounted directly above the ground roll, the segments would swing out of the way when a wrinkle or splice greater than the air gap would pass over the ground roll and drop back into place when the wrinkle or splice had passed. Another advantage of the segmented electrode is the ability to raise center segments and allow strip treating. In earlier electrodes, a thick splice striking the electrode could cause it to be damaged. A corresponding disadvantage is that ozone produced in the corona soon formed aluminum oxide deposits between the segments, thus causing them to remain in the nontreat position. This problem can be overcome to some extent by hardcoating or anodizing the segments. A further improvement is the use of stainless steel as the electrode material. This has virtually eliminated sticking of segments or warpage of the electrode.

A final drawback to this configuration is the possibility of uneven treatment across the web. A substrate having treatment that is not uniform across the web may cause bonding or heat-seal problems in printing, extrusion coating, coating, and laminating. Uneven treatment has been greatly alleviated by bias cutting of segments to prevent strip treating between segments.

The covered roll system using a dielectric covered roll with either a bar or segmented electrode also presented a size problem. In order to properly treat a given web width and

dissipate heat generated during the treating process, the coated roll diameter must increase directly with the total applied power. Heat buildup on coated rolls is very destructive and can only be mitigated by increasing the roll diameter to allow a period of cooling between cyclic positioning under the electrode. In addition, to provide ozone removal and operator safety, the station as a whole must also increase in size as the roll diameter increases. Figure 14 indicates roll diameter requirements as a function of applied power (kW).

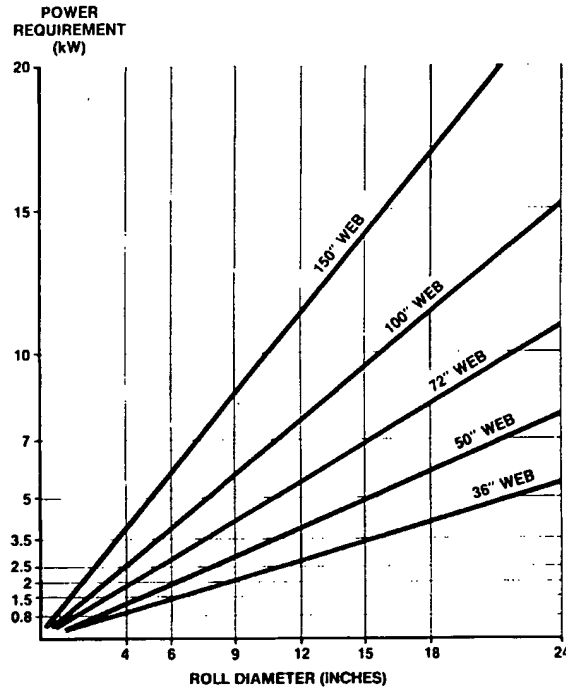


Figure 14. Conventional System - Power Requirement (kW)
VS Covered Roll Diameter (in).

Another method which has been attempted without much success is to use several sets of segmented electrodes which are staggered so that each row of segments covers the air gap from the previous row (see Figure 15). This solution has not proven reliable. Recent tests indicate that significant uneven treatment still occurs.

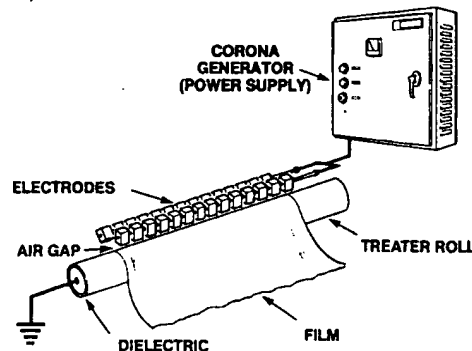


Figure 15. Staggered Segmented Electrodes

Two early electrodes which were attempted involved a glass tube with a metal rod insert and a glass tube filled with steel wool (see Figure 16). This was an entirely new concept because, for the first time, the dielectric cover was removed from the ground roll and placed on the electrode. This early bare-roll configuration promised a great many advantages but was soon abandoned because expansion of the metal rod, due to a rising temperature, broke the glass tube. Even when the electrode was rotated to spread the corona over a 360 degree revolution, neither overheating nor breakage was prevented.

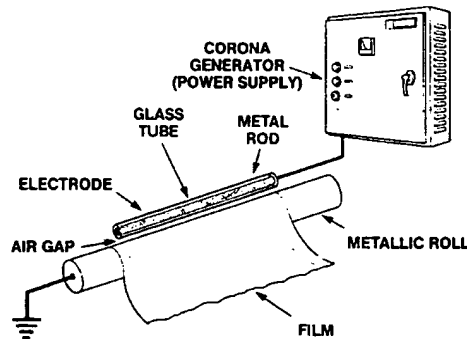


Figure 16. Glass Tube/Metal Rod Electrode

Another serious consideration should be mentioned here. None of the metal electrode covered-roll configurations work when treating conductive substrates such as foils or metallized film, and a very complex form of electrode was required (see Figure 17).

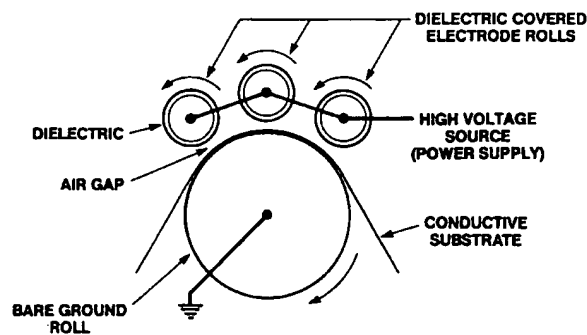


Figure 17. Driven Electrode Rolls

This early bare-roll system consisted of a metal ground roll and a series of dielectric covered electrode rolls that were driven. This is a very expensive, cumbersome method of treating conductive substrates, but it was the only method available.

In 1980, a new configuration of electrode capable of operating on a bare roll was developed which surmounted the basic problems that were experienced up to that point. This electrode achieved the following operational goals (also see Figure 18):

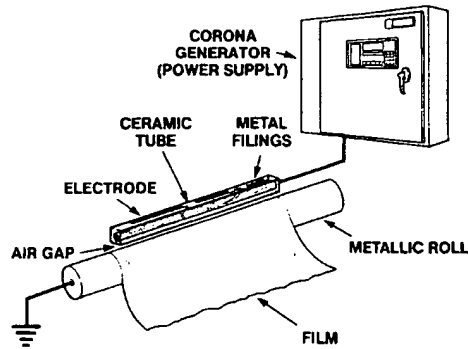


Figure 18. Ceramic Electrode/Bare-Roll.

1. Even corona treatment across the transverse of the substrate.
2. Eliminating the need to adjust the electrode to web width.
3. Eliminating the dielectric roll covering which required frequent replacement and entails an inventory of spare rolls as well as considerable production loss during replacement of a burned-out roll.
4. Allow corona treatment of both conductive and nonconductive webs using a simple system without driven treater rolls. Further, even perforated webs can be treated with this type of electrode.
5. Allow splices to flow through the corona treating station without striking the electrode despite the close position of the electrode relative to the treater roll.

In addition to achieving these operational goals, this new electrode configuration also eliminated the need for a closed cabinet to remove ozone. Conventional corona treating systems require a closed cabinet not only to remove ozone in the operator area, but to prevent electrical shock to operators who are required to work in close proximity of the corona treating station. This recently patented electrode assembly meets all the operational and safety requirements of extruders and converters (see Figure 19).

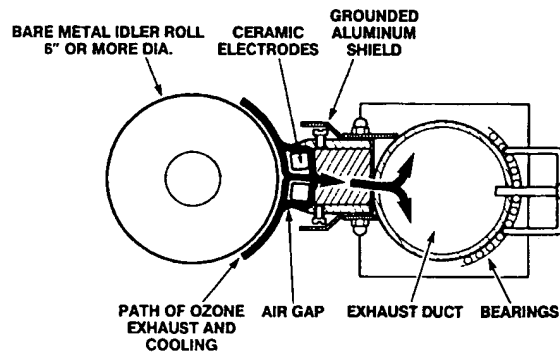


Figure 19. Ceramic Electrode Assembly Cross Section.

Substrates can even be selectively treated leaving specific areas untreated as in the previously mentioned heat-seal applications (see Figure 20). The concept that made this electrode possible was the use of a rectangular ceramic tube filled with irregularly shaped aluminum alloy granules. When these granules heat up, they do not break the ceramic tube since there is sufficient room for their expansion.

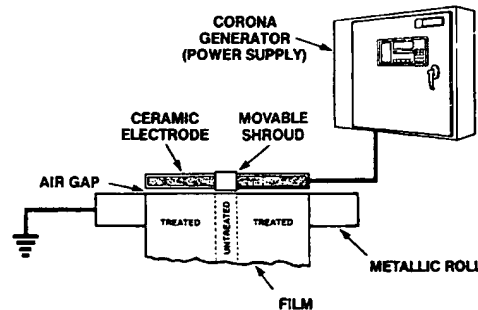


Figure 20. Ceramic Electrode System with Shroud for Strip Treatment.

This electrode is accepted as the latest state-of-the-art in Europe as well as the United States. Hundreds of production lines use this type of system, which proved its ability to treat to high levels while providing long-term reliability.

Why ceramic? It is a material which combines the attributes of dielectric strength with a high electrical power per square inch to enable high treatment levels. A ceramic was developed which allowed twice as much power per square inch to be applied to each electrode. The ceramic electrode achieved this higher treatment level because of its higher dielectric constant and lower electrical reactance. These factors allow the ceramic electrode to provide a higher treatment level for a given applied voltage. Furthermore, since ceramic is less sensitive to high operating temperatures, higher power levels can be applied and maintained to provide consistently higher levels of treatment per electrode.

Any electrode, be it metal or ceramic, has a limit of effective output based upon the total bar area of the electrode. In the past, bar area of a metal electrode was increased by cutting the face closest to the ground roll in a concentric curve to follow the roll face (see Figure 21).

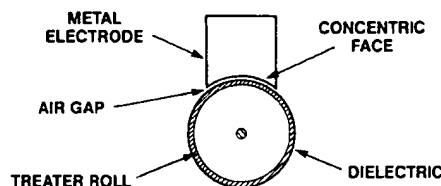


Figure 21. Concentric Cut Electrodes - Side View.

As more and more power is applied to a given electrode, an ultimate limit is reached at which further power applied is wasted. Therefore, as power density requirements increased, corona

treating systems required additional electrodes. The power capacity of the ceramic electrode reduces the number of electrodes by one-half, thus producing a smaller and less expensive station (see Figure 22).

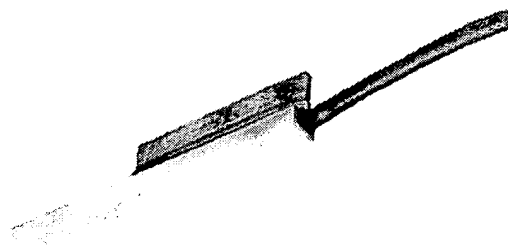


Figure 22. Ceramic Electrode.

Recent advances in dielectric roll coverings and power supply design have made hybrid systems possible that greatly enhance the level of treatment on difficult to treat substrates. Ceramic electrodes with tightly controlled watt density and frequency can be operated over a treater roll coated with a special ceramic (see Figure 23). The result is an improved level of treatment on difficult to treat substrates such as cast film, polypropylene with high levels of slip additives, etc.

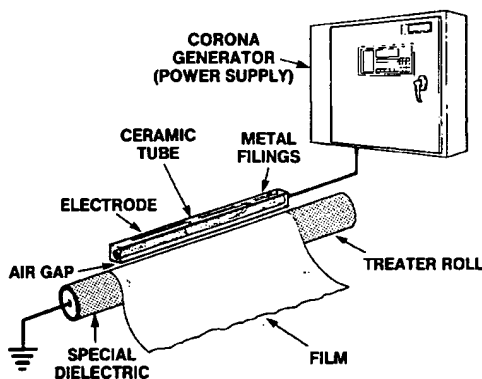


Figure 23. "H" System: Ceramic Electrode/Covered-Roll.

In bare-roll and "H" system treater stations, ceramic electrodes are attached in the assembly to allow removal and replacement in less than 10 minutes. This changeover time is critical when production loss and cost due to downtime can be measured in hundreds or thousands of dollars per hour.

Corona treating electrodes have come a long way — from wire, to segmented metal, to specially formulated ceramic. Each time advancements are made, it would be wise to review what constitutes the ideal electrode. Some characteristics are described here:

1. The electrode must provide a controlled level of even treatment across the web.
2. The electrode should provide treatment to both conductive or nonconductive webs.

3. The electrode must allow a splice to flow through the treater station without damage to the electrode or station.
4. The electrode should provide sufficient bar area or power capacity to minimize the number of electrodes.
5. The electrode must have the physical and chemical strength to survive an industrial environment.
6. The electrode should be easily removed and replaced to minimize downtime.
7. The electrode should provide operator safety without an enclosed cabinet which inhibits threading the web.
8. A method of strip treating should be available in cases where heat-seal areas are required.
9. A provision for purging should be available when systems must be operated in hazardous atmospheres.
10. Air gap requirements should be such that the operator may easily maintain the proper air gap in the production environment.

New advancements should meet these criteria before replacing proven methods. The ceramic tube-electrode fulfills these criteria now, but in the interest of providing the industry with the latest technology available, the search for electrode configuration improvements continues.

Power Supply for Corona Treating

All corona treating installations require a source of controlled electrical power. Low-voltage 60 hertz electrical power is fed into an electrical device which raises the frequency to some higher level. This high-frequency electrical power is applied to a step-up transformer that increases the voltage to some higher level. The high voltage, high-frequency electricity is then discharged from the electrode through the web being treated to the electrically grounded metal roll.

Although the basic principles remain the same, many improvements have been made over the past 30 years which greatly increase the capability and performance of the power supply. The earliest power supplies were motor generator types that proved unreliable for long-term continuous operation due to mechanical breakdowns. These were replaced by power supplies using a Tesla coil and spark gap to generate the high-frequency and high-voltage electrical power. These were an improvement over the motor generator systems but still left much to be desired in reliability due to the erosion of the spark gaps.

Next came solid-state power supplies using transistors as the power output device. Early transistors had a limited output power capacity, however, and these units required as many as 16

transistors connected in parallel to achieve the required power levels. Although transistors are generally very reliable solid-state devices, the larger number of components required caused a proportional increase in the chance of a random failure.

The natural evolution of power supplies then led to the development of an inverter using silicon controlled rectifiers (SCR's) as the power output device. SCR-type inverters have been in widespread use for the past 25 years and have proven to be very reliable.

Recent advances in transistor technology have led to a new generation of corona treating power supplies which provide increased power output in smaller sized enclosures. The ability of these new power devices (IGBT's) to handle higher current levels yet provide high speed on/off switching through logic control allows more precise control of treating power and frequency.

The advent of logic controllable power devices allowed the use of programmable microprocessor and minicomputer chips that provide reliable treatment levels on a variety of substrates. Improved control circuits for corona treater power supplies are now available which increase the consistency of corona treatment for enhanced adhesion of the extrudate to the substrate and, in post treating applications, of inks, primers, coating and laminants to the extrusion coated surface. Housed on a microcontroller circuit board and incorporating microcomputer technology, this advanced control assures corona treating accuracy and consistency by automatically tuning the power supply power and frequency to all variables such as electrode, roll type, web thickness, and air gap (see Figure 24).

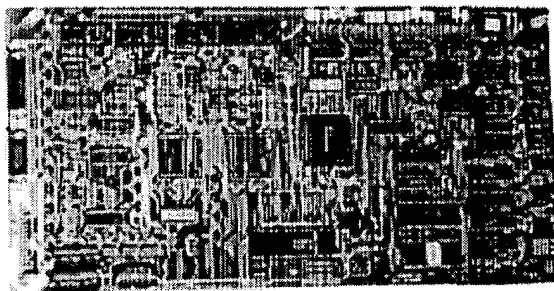


Figure 24. Microcontrol Board.

Corona Treating Applications

The majority of extruders contain corona treating systems. Normal practice in the past has been to treat film at the time of extrusion and ship it to the converter for printing, coating, and laminating without further treatment. Since film is easier to treat immediately after extrusion, this has always been considered the optimum location for the treater.

Recent years have brought a distinct trend toward in-line treatment or retreatment on the coating, laminating, or printing machine. One of the factors contributing to this trend is the fact that treatment levels decay somewhat with time and can be seriously weakened by contact with idler rolls during subsequent machine operations. There is also a practical limit on the treatment level that can be applied to a film prior to winding if blocking is to be avoided.

Film suppliers have traditionally provided treatment levels in the 36-42 dynes/cm range. For example, treatment levels in this range are adequate for flexographic printing using solvent-based inks and are just barely acceptable for bonding with solvent-based adhesives.

However, extrusion coating on milk carton stock, paper, foils or even pre-treated film frequently requires treatment or retreatment on the coater just prior to applying the extrudate. Tests of bonding strength have verified this requirement in numerous cases.

Pollution reduction measures such as water-based inks and adhesives and 100 percent solids or high-solids adhesives have necessitated the placement of corona treating equipment on many converting machines (13) (15). This is partly because the new inks and adhesives have a higher surface tension and don't wet the film as well as solvents, and partly because of fatty-acid slip additives present on the surface of the film.

Initial treatment on the extruder is accomplished before much of the slip additive has migrated to the surface. The slip additive has relatively poor wetting characteristics and can cause problems in bonding unless subjected to a second in-line corona treatment. Even before the advent of new types of adhesives and printing inks, a high percentage of converting machines were equipped with corona treaters simply as a quality assurance tool for avoiding problems caused by inadequately treated film from a supplier.

The problems of high-slip additives, loss of treatment over time, and the movement to water-based and radiation cured materials affect the treatment levels required during post-treatment of the extrudate coated side. Suppliers of substrates to converters for further converting operations are pressured for high levels of treatment which:

1. Deteriorate faster over time (16).
2. Become masked by additives, especially slip additives, migrating to the surface (12) (17).
3. Either cause blocking of the wound substrate roll or are insufficient for converting operations using waterbased inks, coatings, or adhesives. (14) (16).

As a result, in-line retreatment may be required by the converter to achieve adequate bonding.

Constant development of new plastic materials, printing inks, and adhesives, as well as a wide diversity of applications for the corona treating process, dictate that individual treatment level requirements be determined according to the product application and end-use requirements. Specifications for treatment level can often be obtained from the raw materials supplier or the machinery manufacturer. If treatment level data are not available from these sources, actual trial using a corona treater will establish the minimum required treatment level. Most manufacturers of corona treating equipment have laboratory setups available for this purpose.

Experience with converting machines has indicated that there is an upper limit on treatment level. Very high treatment levels create polar groupings which are hydrophilic and may absorb excessive water, causing a reduced bonding layer at the substrate surface. In addition, over-treatment may produce low molecular weight products at the surface which do not maintain adequate bonds to the bulk substrate.

Very difficult to treat substrates such as polypropylene, very wide web widths, or very high-speed lines may require high power levels spread over numerous electrodes. Treaters with output ratings of 30 kW or more are available, so there is no application beyond the power range of present day corona treating equipment. It is, however, unwise from a cost standpoint to purchase treating equipment with a capacity beyond that which is necessary.

Thermal bonds such as those made by an extrusion coater or by a thermal laminator are greatly improved by corona treatment. In extrusion coating, the paper, foil or film substrate is treated just prior to the extrusion nip. Precisely why the surface of paper is more receptive to bonding by extrusion coating is not known, but it is a common practice and, in fact, does promote stronger bonds at higher line speeds. Foil surfaces are thought to be improved by chemical change of rolling oils left on the surface from previous forming operations. In the case of annealed foil, treatment has an effect on the residues of the oils. Thermal laminating, in which two plastic webs are bonded by heat and pressure, requires treatment of both webs to a level above 40 dynes.

Ozone Treatment

The introduction of ozone in proximity to the extrudate also assists in the bonding process. Specialized ozone generators have been developed just for this purpose (see Figure 25).

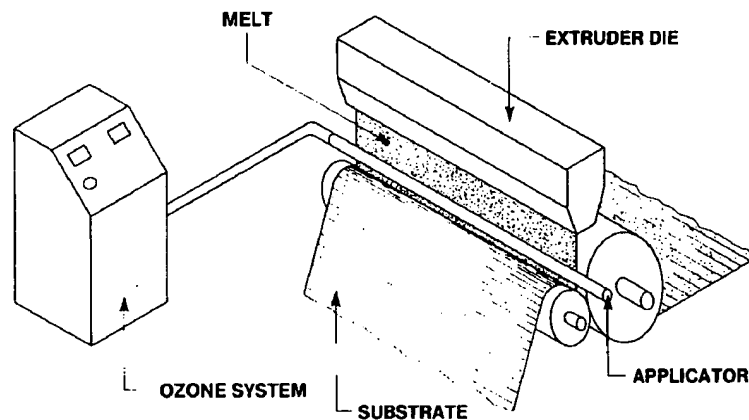


Figure 25. Ozone Treatment System.

The bond strength between substrate and extrudate in extrusion coating greatly depends on line speed, gap, and extrudate temperature, which affects the degree of oxidation of the melt. Generally stated, the higher the melt temperature of the extrudate, the better the bond strength.

Ozone treatment can be used to:

1. Increase line speeds
2. Increase bond strength
3. Reduce extrusion temperatures without sacrificing bond strength

4. Reduce extrusion temperatures to preserve heat sealability and reduce odor
5. Create bonds that cannot be made with just temperature, air gap, corona, and primer.
6. Reduce air gap (dwell time).

However, only in a few instances can the ozone system be considered an alternative method to corona/flame treatment and/or chemical priming. In most of the applications experienced so far, ozone treatment is used in combination with either or both of these methods. While corona treatment and primers prepare the substrate for a good bond, ozone treatment affects the extrudate only. A melt that is fully oxidized (usually at extrusion temperatures above 610 degrees F) cannot be further improved by exposing it to ozone, yet higher line speeds under these conditions are feasible without sacrificing bond strength (Resources: 18).

Sizing: The Critical Element for Effective Corona Treating

The purpose of this section is not to provide detailed information that will allow the reader to size a corona treating system for every specific extrusion, coextrusion or extrusion coating, or laminating application. To achieve that goal would require more space and time than this chapter can cover. Rather, a series of application parameters affecting system sizing will be examined in order to provide the reader with a systematic procedure for evaluating corona treating systems. Further, readers will learn ways in which they can increase effectiveness, reduce costs, and obtain the greatest value when purchasing a corona treating system.

Basic System Rating

When selecting an electric motor, most purchasers understand that horsepower alone does not provide sufficient data for a particular application. Data such as starting torque, operating speed, breakdown torque, and intermittent operation also affect motor selection. Corona treating systems are analogous. Historically, the starting point for treating system sizing has been power supply kilowatts and treater station width, which then determines the maximum web width that can be handled. However, as with horsepower in the case of motor selection, this does not provide sufficient data for a specific application.

The ultimate goal of any surface treatment system is to increase the product's surface tension measured in dynes per centimeter, which then increases the wettability and adhesion characteristics of the surface. Corona treating systems achieve this by applying a given level of power over a certain period of time to the surface. This power-time parameter is measured in watt density, which is defined as watts (power) per square foot per minute (see Figure 26).

$$Wd = \frac{PS_w}{WW_n \times LS_{tpm} \times NST}$$

where:

Wd = watt density (watts/ft²/min)
 PS_w = power supply (watts)
 WW_n = web width (feet)
 LS_{tpm} = line speed (ft/min)
 NST = number of sides treated

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Figure 26. Corona Treating System Parameters.

Although watt density applied is directly related to the increase in dyne level (surface tension), the relationship is not linear, and the relationship is different for each type of material treated. The subtleties of this relationship will be discussed later. For now, it is enough to know that, generally, the greater the applied watt density, the greater the increase in surface tension.

Conditional Parameters of Watt Density

Watt density as a control function appears to make system sizing relatively easy until one considers all the parameters that affect watt density. These parameters can be broken down into two categories: system parameters and material-process parameters. System parameters are governed by corona system and machine design. Material-process parameters are governed by material and process requirements.

System Parameters

The most obvious system parameters are power supply size (kW) and station size (web width). Applied watt density is directly proportional to power supply size in watts and inversely proportional to station size (web width), in feet (see Figure 25). This means that to maintain a required watt density, if the web width is doubled, the watt rating of the power supply must be doubled. This straightforward relationship is complicated by two factors: line speed and the capacity of the electrode to handle a given level of applied power.

Each type of electrode, whether wire, metal bar, metal shoe or ceramic covered, has an upper limit on the amount of power it can accept per unit length. If, to achieve a given watt density, the power supply kW increases beyond the electrode's maximum rating, additional electrodes must be added. Further, an increase in the number of electrodes required may cause an increase in treater roll diameter. Both of these factors may increase the physical size and cost of the treater station required for the application.

Line speed is the second system parameter that complicates the sizing calculation. On a given system, the higher the line speed, the lower the maximum watt density that can be achieved. Being inversely proportional to watt density, line speed has a significant impact on system sizing and cost.

Material-Process Parameters

The most obvious material-process parameters are the basic substrate material composition and the process being performed (extrusion, extrusion coating, printing, etc.). Upon analyzing these factors in detail, their impact on corona treating sizing becomes increasingly complex.

Begin with substrate material composition and assume that the materials are all "barefoot," i.e., virgin material without any additives. The surface tensions of typical substrates used by the extrusion and converting industries are provided in Table 3.

Table 3 evidences an immediate problem as most materials are defined by a range of typical surface tensions. The various surface tension values of a given material may be explained by

several contributing factors such as method of manufacture (blown film vs. cast film), variations in die temperature at time of extrusion, and type and amount of impurities which always exist in even the highest quality film. If a given material is treated at a given watt density, its surface tension will be increased. However, both the ultimate surface tension achieved and amount of increase are dependent upon the material's starting surface tension. For example, applying a watt density of 1.2 to PET at 41 dynes may raise it to 46 dynes, but applying that same watt density of 1.2 to PET at 44 dynes may raise it to only 48 dynes. Although the final dyne level is higher in the second instance, the incremental increase is less because of the starting point dyne level. Further, the variation of barefoot material response to corona treating is compounded by additive loading. The impact of additive loading will be discussed later in this section.

As mentioned earlier, different materials or substrates react differently to corona treating. Some materials, such as some polyesters, accept treatment readily and will exhibit rapid increases in surface tension under relatively low watt density levels, say 0.9 to 1.2. Other materials, such as polyethylene, accept treatment less readily but will exhibit a significant increase in surface tension under moderate watt density levels, say 2.0 to 2.5. Finally, some materials, such as polypropylene, are difficult to treat and may exhibit only moderate increases in surface tension under relatively high levels of watt density, say 2.5 to 3.0.

Variations in material response to corona treating are further compounded by differences in process parameters. It is well understood that extrusion, extrusion coating, and extrusion laminating require different levels of treatment to achieve acceptable product quality and production levels. However, it may be less obvious that extrusion coating of a given resin, say PET, will produce a substrate with different posttreatment response than the same resin undergoing cast film extrusion. A further complication which increases watt density requirements significantly is the combination of cast extrusion with tenter frame. The differences in corona treating response in these cases are due to the following elements:

1. Molecular structure variations as a result of the extrusion process.
2. Temperature of the substrate at the time it enters the corona treating station.
3. Location of the corona treating station relative to the point of extrusion.

The cast film application highlights the increasingly low response to corona treating caused by molecular structure, temperature of the substrate, and location of the treater station (see Figure 27). In this application, the film is extruded, cast onto a chill roll, and then may be biaxially stretched while being heated before being wound.

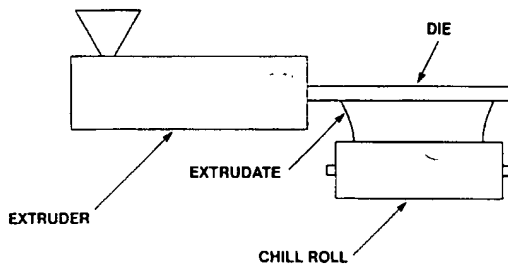


Figure 27. Beginning Of Line (End View)

Corona treating can occur immediately after the chill roll on either the warm or cold side of the film (see Figures 28 and 29).

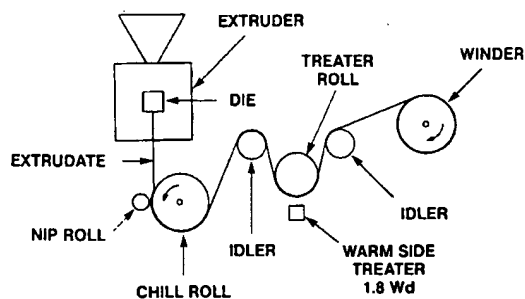


Figure 28. Line Schematic - Warm Side Treating

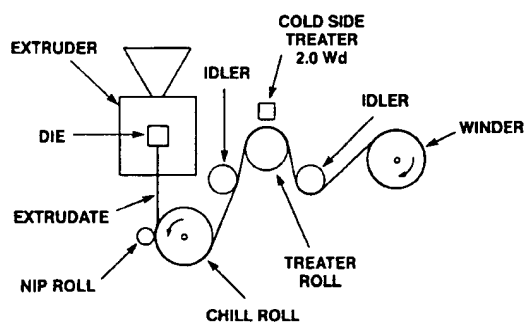


Figure 29. Line Schematic - Cold Side (Chill Roll Side) Treating

On oriented or biaxially oriented film, the corona treater is placed after the orienter (see Figure 30). Watt density values (Wd) are shown for each instance. However, the exact Wd value is not as informative as the relative differences between values shown at each location.

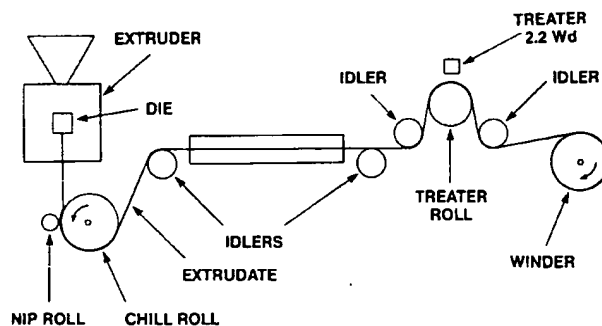


Figure 30. Line Schematic Biaxially Oriented Film Treating

Treatment of blown film experiences similar differences in required treatment level based upon the position of the treater station and temperature of film at the time it enters the station. Figures 31, 32, and 33 demonstrate that a lower Wd will raise a given film to a given surface tension level when the treater station is located at the nip at the top of the tower than when the treater station is located halfway down the tower or at the bottom of the tower just prior to the winder. Note that the Wd level required does not change between Figures 31 and 32. This is because the film temperature between these points is essentially constant.

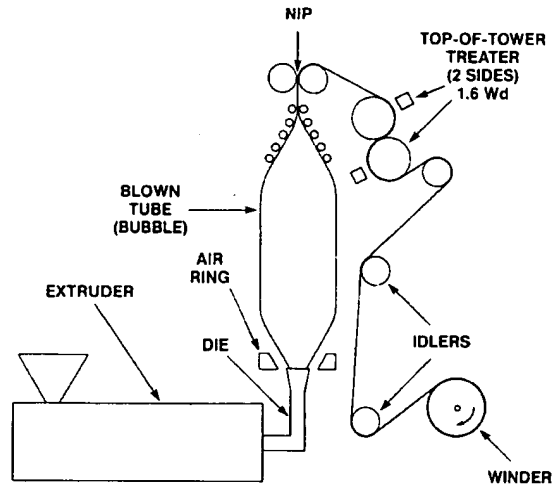


Figure 31. Line Schematic - At-Nip Treating

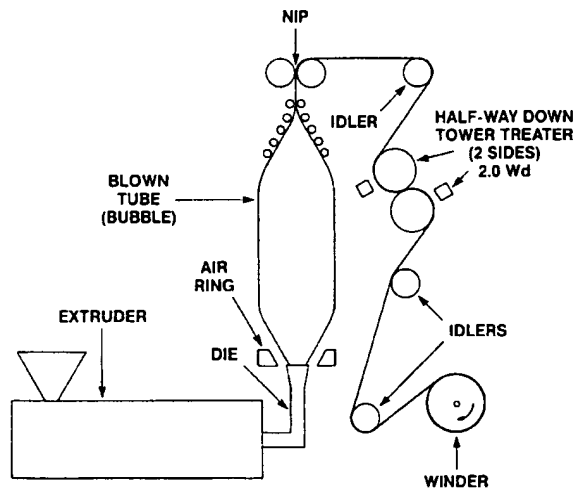


Figure 32. Line Schematic - Half-Way Down Treating

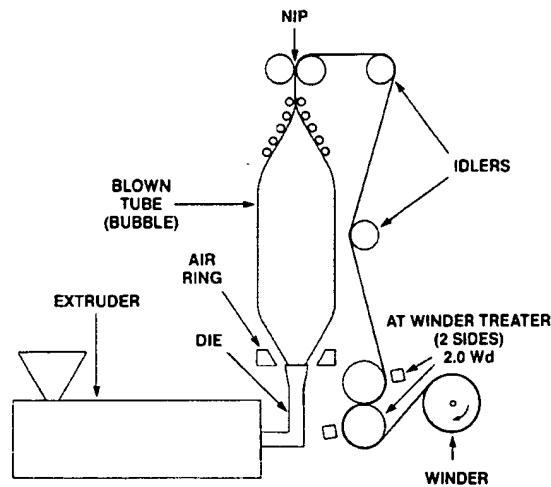


Figure 33. Line Schematic - At Winder Treating

Other Factors Affecting Watt Density

So far, the discussion of watt density requirements has addressed the major factors of treatment system design, application requirements, and basic material (web) composition. There are a number of other factors which impact treatment response and the ability of a web, film, or other substrate to maintain a treatment level. These other factors include retreatment, time, and additive loading (see Figure 34).

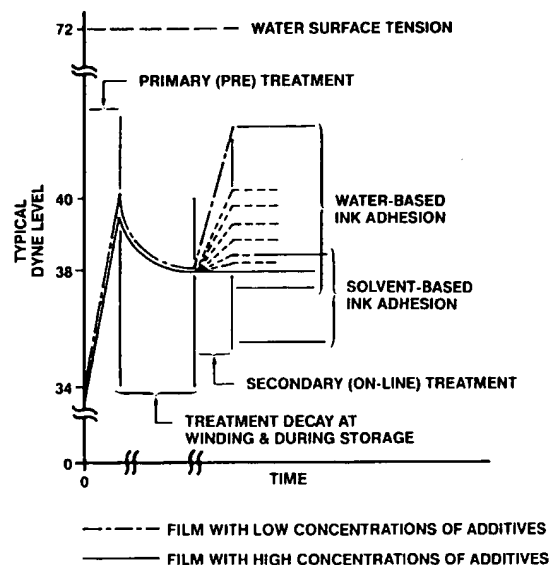


Figure 34. Factors Affecting Watt Density.

Retreatment

Retreatment is the situation in which a previously treated web is treated again in-line just prior to the completion of a converting process. For example, a film that was treated at the time of extrusion may be treated again on a coating line just prior to the laydown of a water-based coating. This retreatment process is not unusual when dealing with film containing some additive loading that is stored for a period of time between its extrusion and the coating process.

Retreatment is more common when water-based or radiation curable coatings are used as opposed to solvent-based coatings which wet-out and adhere more readily. For example, a film with a surface tension of 31 dynes as extruded may be treated to a level of 40 dynes on the extruder. After shipment and storage, the effect of time and additive loading may reduce the film's surface tension to 36 dynes or less. At this level, solvent-based coatings may well provide a high-quality product without further treatment. However, a water-based or radiation curable coating may require that the film be retreated to raise its surface tension to 40 or more dynes. Experience demonstrates that, for a given surface tension improvement, retreating previously treated film requires a lower watt density than treating a film that has not been pretreated.

Additive Loading

Additive loading, the amount of additives in parts per million (ppm) contained in the film, has a significant impact on a film's ability to be treated and to retain the effect of corona treatment. The initial impact of higher additive loading is to require increasing watt densities to raise the film's surface tension by a given amount. Furthermore, higher additive loading will reduce the film's ability to maintain the effects of corona treatment. This is due to the tendency of additives to bloom or migrate to the surface and mask the effect of corona treatment. It is commonly held that additives will more readily migrate to a film surface that has been treated.

Time

Treated surfaces will lose treatment over time (16). This is true for all methods of surface treatment and all films, even those with no additives. The amount of treatment loss is dependent upon the type of film, the level of treatment, the type of treatment, and the amount of time. One study done on an extrusion coating application demonstrated that between 1 and 7 percent of treatment was lost in the first nine days after treatment. By 37 days after treatment, between 32 and 38 percent of the treatment had dissipated (8).

Sizing Considerations

To adequately size a corona treater for a given application, several machine and application variables must be closely studied. As some applications cover a range of materials, it is wise to determine the worst case material and size the equipment for that material. Some parameters may require an examination of both the minimum and maximum to properly select components.

Treater suppliers have developed data sheets which systematically present all of the information that may impact treater system sizing. Figure 35 is an example of a data sheet for general treater applications. Information on the parameters discussed, as well as some not specifically covered in this section, appears on the data sheet. Each item affects the physical or electrical design of the system and, ultimately, the ability of the system to meet the performance and long-term reliability requirements of the application.

Figure 35. Treater Quote Data Sheet

Much has been said about various electrode configurations and different frequencies having the ability to treat film more efficiently. Extensive field experience and laboratory trials have indicated that, regardless of the shape of the electrode or the frequency of the electric current, it is the number of watts applied to the film that ultimately determines the treatment level. The main consideration in an electrode design is that it should provide a uniform distribution of corona and be of adequate size to permit full rated output from the power supply. To properly match the electrode/roll load, the power supply must be able to adjust both power and frequency output. Newer microcomputer-based power supplies can automatically match output frequency to the load's resonant frequency and transfer rated power in an efficient, effective manner.

In keeping with the modern trend to eliminate operator involvement to the greatest degree possible, the power supply should also automatically match varying web widths. Some power supplies are very sensitive to changes in load such as different film thicknesses or electrode lengths. These power supplies are adequate for fixed-width and fixed-thickness films, but require tuning by the operator when variables are introduced. The power supply should also be equipped with a loss of treatment sensor that sounds an alarm if power output falls below the desired level. This alarm will immediately alert the operator and avoid production of scrap due to the treater not putting out adequate power.

Two optional features which may be beneficial include a remote control station which places the treater controls at a location convenient to the operator, and a zero-speed switch which shuts the treater off when the line stops.

Another important consideration is whether or not conductive webs, such as metallized films or foils, are currently being processed on the machine or will be at some point in the future. Conductive webs require that the insulation be placed on the electrode. The two basic types of treater stations for accomplishing this are the rotating covered roll electrode and the ceramic electrode. The covered roll type stations use multiple rotating dielectric covered rolls mounted around a bare metal ground roll. Earlier in this chapter, the difficulties in maintaining dielectric covered rolls were pointed out. Since the foil treating station uses multiple covered rolls, the problems are compounded. Stations of this type are becoming obsolete. The ceramic electrode treating station is the only sensible method in current use for treating conductive webs.

If a treater station is to be located in an area where solvent fumes are present, it will be necessary to purge the system to prevent explosion hazards. Generally, nonexplosion proof-treating stations are much more convenient to thread-up and maintain than purged stations. If possible, the treater station should be located outside of the hazardous area. If this is not possible, however, the station must be equipped with gasketed doors, interlocks, and timers for proper purging from an air source.

The normal air gap setting between electrode and roll for most corona treating systems is .060 inch. This air gap distance can be varied to permit treatment of thicker materials such as foam and sheet. Air gaps up to one-fourth inch are often used. A well-designed treater station should have air gap adjustments external to the treater station. This permits air gap adjustment while the equipment is in operation and eliminates potential harm to plant personnel from electrical shock. The electrode should also be mounted in a way that permits it to pivot out of the way to clear an obstruction on the web such as a splice.

Since power supplies used in corona treatment produce potentials as high as 10,000 volts, extreme care should be taken in operating and installing the equipment. The high-voltage transformer should be located as close as possible to the electrode to avoid unnecessary personnel exposure. The optimum arrangement is to have the high-voltage transformer be an integral part of the treater station. With stations of this type, all high-voltage wiring and connections are internal to the treater station, and no high-voltage wiring is done at the time of installation. If for some reason it is not possible to mount the high voltage transformer directly on the treater station, the high-voltage wire should be run through a metal pipe via plastic spacers providing about two inches of clearance between the high-voltage wiring and the inside wall of the pipe. Precautions

taken with high-voltage wiring will not only provide operator safety, but will eliminate one of the most common sources of failure in corona treating systems: high-voltage shorts to ground.

Corona discharge generates ozone, which is highly corrosive and toxic in concentrated amounts. A good treater station should be constructed so that all parts exposed to ozone are made with materials such as aluminum, stainless steel, or protective plating that resist corrosion. An exhaust system with sufficient capacity to remove ozone from the plant environment must be provided.

Effects of Time and Contact on Corona Treated Surfaces

It has long been known that some of the beneficial results obtained by the corona treatment degrade after treatment. It has been felt that the primary cause for this loss is that any subsequent rubbing of the treated surface over idler rolls, reel drum, etc., tends to wipe off the treatment. This effect can be demonstrated by wiping selected areas of a sample before running the dyne test. It has also been demonstrated that natural aging of the product, in roll form will reduce the treatment, and it has been theorized that this is a result of diffusion of the radicals formed during treatment (18) (19). Both of these causes are minor, however, when compared to the primary cause for the loss of treatment.

It should be pointed out that once the final converting process has been performed, i.e., printing, coating, or laminating, the beneficial results of corona treatment's improved bonding are permanent. In other words, the ink will not begin to peel over a period of time, nor will two substrates delaminate. Degradation of treatment occurs only between the time of treating and the following converting process.

Recent studies have revealed that almost all loss of treatment occurs immediately after treatment when the treated side of the sheet contacts the opposite side. This will happen at the end of the machine whether the product winds up in roll form or is sheeted in-line.

The continued loss of treatment, between the time of manufacture and the time of use, has become a major problem for the supplier. In the attempt to assure their customers of a satisfactory product, manufacturers have resorted to higher and higher levels of initial treatment. This has not adequately solved the problem since the higher the initial treatment level, the greater the loss. The final result, at the time of use, is only a slight increase in dyne level when compared to a more moderate initial treatment. These attempts to treat to higher levels have created problems for the supplier and often result in an off-quality product for the end user. A partial list of these problems and their causes appears in Table 5.

It is known that a less glossy finish will result in higher dyne tests, but this does not result in improved adhesion. The finish of the polyethylene surface is controlled by the finish of the chill roll. A lower gloss finish is created by utilizing a chill roll with microscopic pits in the finish which in turn creates microscopic bumps on the polyethylene surface. This type of finish will, in fact, give higher dyne test results. Unfortunately, it does little to improve ink adhesion. The reason lies in a fallacy in the test procedure. After the dyne solution drawdown is made, the dyne reading is measured by the time required for solution crawl or beading to be exhibited. A surface with a multitude of microscopic bumps will mechanically impede the crawl of the test solution.

This will naturally be interpreted as a higher dyne reading, but this mechanical hindrance does not have an equal effect on ink adhesion.

Tests conducted on samples obtained immediately after the treater station, as well as in the roll, have revealed losses as high as 17 dyne points. The work also shows that the amount of loss is dependent upon two factors: the amount of the initial treatment and the composition of the surface contacted by the treated surface (see Table 6)

The samples obtained before contact with the opposite side were taken on-the-fly during actual manufacture of the product. Additional on-the-fly samples down the length of the machine showed no loss of treatment after contacting and passing over following rolls. Dyne test results remained at the same level as immediately after the treater until the point of contact with the opposite side.

Additional work has shown that when the surfaces are pulled apart and then brought back into contact with each other, further loss occurs. It has long been known that dyne readings are reduced by rewinder operations. It was thought that this was due to the treated surface contacting the machine rolls during rewinding. However, on-the-fly sampling at the rewinder reveals the same results as were obtained on the production machine. That is, there was no dyne loss due to rubbing on the machine rolls, but loss occurred at contact of the web surfaces. Approximately 90 percent of the total loss occurred at first contact, with the remaining loss occurring at second contact. It was not possible to measure the loss suffered at subsequent contacts. However, other data indicates that each subsequent contact reduces the treatment to a lesser and lesser degree until the test results approach the same level as an untreated sheet. It appears that no matter what is done in normal operations, traces of the original treatment will always remain.

An interesting additional point is that when both sides are treated, both sides lose in dyne test, i.e., the treatment is not transferred, but is partially destroyed on both surfaces when sides come in contact with each other.

The higher the level of treatment and the greater the degree of oxidation of the opposite side, the greater the attraction of the two surfaces and the greater the opportunity for blocking. The two surfaces have a substantial attraction for each other and can be pulled apart only by rupturing the chemical bond that was created on contact. Often, during high-speed unwind, a singing sound can be heard as the two surfaces are pulled apart.

Further bonding, to a much lesser degree, occurs when the surfaces are recontacted, but more damage is then done to the treatment. It is believed that this is due to recontact at a slightly different point where more radicals on the treated surface and more oxygen on the opposite surface are available for mutual bonding.

This bonding, with subsequent ripping apart, alters the reactive end of the molecule on the treated surface. This altered end does not contribute to increased surface tension. Unfortunately, it is this altered molecule that has been so painstakingly examined in past research work.

If a polyethylene contains additional components, such as slip additives, the initial treatment is reduced over time as these additives bloom to the surface and partially mask the radicals formed during treatment. However, it is felt that when polyethylene contains slip additives, treatment at the point of use is more effective if the sheet had been treated at the time of manufacture.

It is now apparent that there is only so much that the material supplier and corona equipment

manufacturer can do to furnish a suitable product for the final end user. When they attempt to treat to higher levels, the majority of the treatment is lost immediately upon contact, but all the negative conditions mentioned still exist. However, it is also apparent that a small portion of the initial treatment remains regardless of what normally happens to the sheet after manufacture. This small residual makes further moderate treatment more effective. It is analogous to a primer coat of paint.

Control Development and Statistical Quality Control (SQC)

Recent papers on the new movement in quality control and quality management have placed emphasis on a total approach, i.e., total quality control (TQC) (21) and total quality management (TQM) (22). There is no question that management attitudes and assignment of resources is critical to successful implementation of quality control (QC). However, the key element in QC is measurability. If a parameter is not measurable, it cannot be subject to control. Therefore, the real key to total quality management (TQM) lies at the bottom of the pyramid (see Figure 37). There each parameter in the end-item product is ultimately defined in detail. That definition must include not only a nominal measurable value but an acceptable measurable tolerance. This requirement for definition applies not only to materials, but also to the processes which turn the materials into the end product.

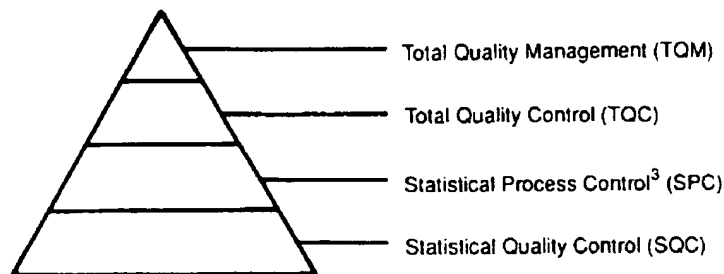


Figure 37 - Total Quality Management Pyramid.

Corona treating is just such a process, and although the effects of this process can be quite visible in the end product, the corona treating process itself is not always measurable in the end product. What this means is SQC of the corona treating process must be accomplished on-line, be accomplished in real-time, and must be subject to recorded and measurable parameters.

As a result, SQC of corona treating requires statistical process control (SPC) which, in turn,

requires the ability to control a measurable parameter and record a significant amount of precise data quickly in real-time.

Recent developments in microprocessor based digital technology have been introduced into corona treating and have greatly enhanced user-operator control of the process. For the user, these control developments have meant a new level of quality control by allowing on-line, automatic control of watt density and data outputs which permit SQC analysis of potential problems. To achieve this, the following control features are incorporated.

Computer-Aided Operation and Diagnostics

To ensure a corona treating system is operating properly, it must provide outputs of various operating parameters within the system. Until recently, this required the use of various pieces of test equipment and a trained technician. Today's technology allows this data and other process and diagnostic information to be captured and displayed on a local or remotely located information panel (PLC). The ability to display this information, along with numerous operating features, makes this system a valuable tool for data collection and troubleshooting purposes.

Microcontrol Capabilities

The introduction of microcomputer/ microcontroller devices has allowed the power supply to precisely control output power and frequency. In addition, it has provided the operator with a level of information display and control not previously available (see Figure 38). The information is displayed via a discrete LED status panel or on an 80 character display panel (see Figure 39).

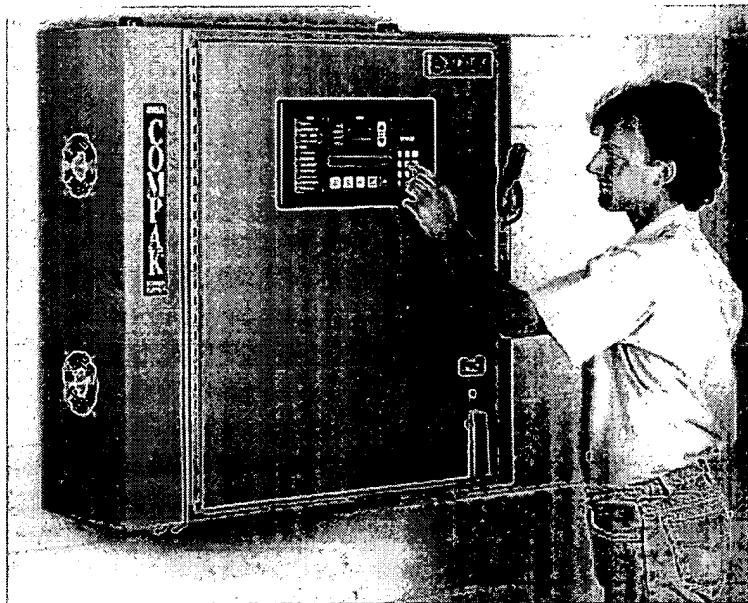


Figure 38 - Easy Operator Control Panel.

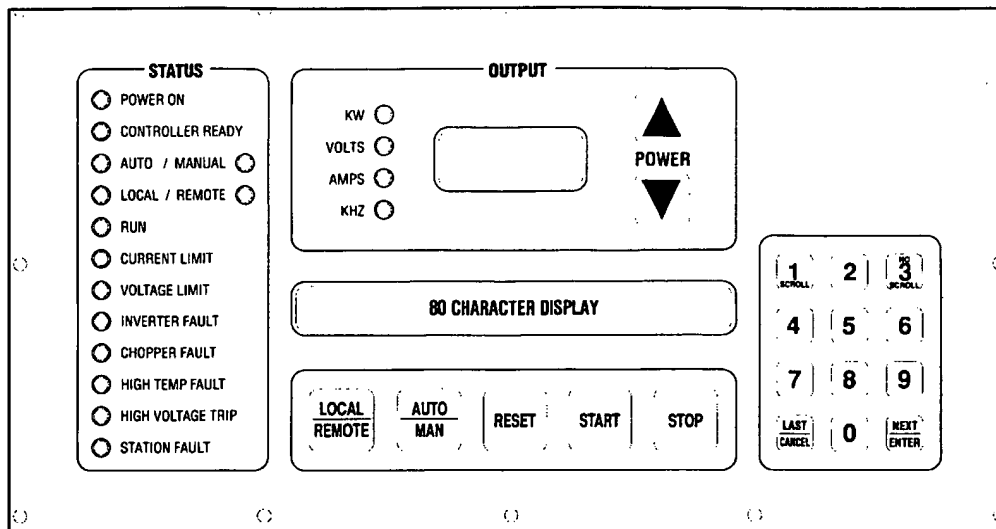


Figure 39 - Microcontroller: Monitor & Control

In addition to the various inputs and outputs which can be monitored and displayed, there are many other features available when using a microprocessor based control and display system. They include the following:

1. Watt density control.
2. Skip treat.
3. Tachometer start and stop
4. Computer interface.
5. Troubleshoot indicators.
6. Diagnostics.

SQC Watt-Density and Corona Testing

Not all end-product parameters lend themselves to on-line quality control. For that reason, all converters maintain some form of laboratory testing. The laboratory can test raw materials, substrates, and coatings for adherence to manufacturer specifications, and can test converted products to assure good adhesion of coatings to substrate, strength of lamination, etc. These tests are critical to the converter's ability to deliver a quality product to its customers. However, in many instances this form of testing does not prevent a poor product from being produced, but merely prevents a poor product from being delivered. The result can be considerable waste in the form of scrap that cannot be shipped.

Raw materials, substrates, and coatings, that pass receiving inspection must still be married in the converting process, and the process itself may result in the production of poor quality product. Discovery of final product deficiencies in the laboratory cannot be considered the ultimate goal of a total quality control system.

Process problems must be defined on-line and in real-time to ensure correction before the completion of product production. Corona treating as a process that can be critical to good quality production must therefore be made a part of statistical process control.

Of course, there are many other process parameters which affect product quality, and converting machinery builders are addressing the implementation of process control methods which ensure on-line, real-time measurement and regulation of critical process parameters (23).

As previously stated, the corona treating process raises the surface energy level of substrates to improve wettability and adhesion characteristics which ultimately determine the resultant coating and lamination quality (5). Surface energy level is measured in dynes per unit of length, usually centimeters. Today's technology does not allow the measurement of surface energy directly on-line in real-time. Surface energy measurement is possible in the laboratory through the use of dyne level solutions (10) and contact angle measurement (11) (15). As stated earlier, measurement of surface tension in the laboratory would not be sufficient for adequate SQC for the following two reasons:

1. Surface tension is transitory. It degrades over time on all substrates and, on some substrates, degrades considerably over short periods of time. Therefore, a laboratory measurement of surface tension may not yield an accurate reading of what the surface tension was at the time of treatment.

2. Any laboratory measurement of the effect of corona treatment being implemented in-line would provide data too late for in-process quality control.

This dilemma has a rather straightforward solution since, with corona treatment, there is an in-line process parameter directly proportional to surface tension which can be measured in-line and in real-time. That process parameter is watt density per linear unit squared. As a result, in-process statistical quality control can be implemented by a control system that instantaneously controls watt density and outputs deviations throughout the production run.

Auxiliary Equipment

Ozone (O₃) is a necessity in some processes and merely a byproduct in others. But in all cases, ozone must be removed from the work area or it will cause health hazards and serious corrosion problems.

Until recently, only one solution was possible for ozone-contaminated air; it could be exhausted into the atmosphere. Recently, however, local, state and federal regulations have been passed which sharply limit venting ozone to the atmosphere. The Environmental Protection Agency, which has not directly regulated ozone, is now considering Federal standards for O₃ release.

By converting ozone into oxygen, ozone decomposition units reduce air stream ozone contamination to less than 0.1 ppm, a safe level in the work area as defined by OSHA and for venting to the atmosphere as limited by the toughest clean air regulations.

A catalytic ozone decomposer converts ozone (O₃) into oxygen (O₂). The unit consists of a particle filter, a prefilter media and metal oxide catalyst bed that reduces an input ozone level of up to 150 ppm to less than the OSHA limit of 0.1 ppm at the designated flow rate (see Figure 40).

How Ozone Decomposition Works

Ozone-contaminated air (treater exhaust) is input at the top of the unit and flows through the particle filter. Here, particle matter and dust are removed to ensure they do not contaminate or clog the catalyst bed. The exhaust stream then moves through a prefilter media which neutralizes certain extrusion and converting gases and vapors to prevent them from contaminating or masking the ozone catalyst. Finally, the ozone contaminated stream moves through the bed of metal oxide pellets which converts the ozone (O₃) into oxygen (O₂). The exhaust stream can then be vented into the atmosphere.

Ozone and other toxic gas levels must be monitored on a regular basis to confirm that no health hazards exist and to determine when the particle filter, prefilter media or catalyst should be changed or reactivated.

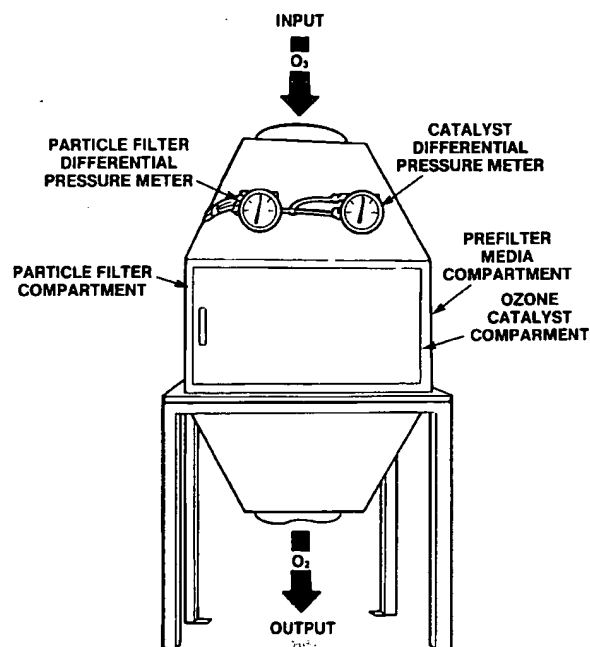


Figure 40 - Ozone Decomposition Unit.

Conclusion

The current state of the art in surface treatment provides practical solutions to the need for increasing the surface tension of substrates in the production environment. However, the technology of surface treatment must advance on two fronts to meet the needs of constantly changing materials (both substrates and coatings) and production parameters. First, the science of surface treatment must better define the mechanism by which surface treatment affects surface characteristic changes at the molecular level. Second, the technology of surface treatment must advance to provide adequate treatment levels at ever-increasing web widths and line speeds dictated by the economics of production.

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**Table 1. Concentrations of Formamide: Cellosolve_{TM} Mixtures
Used in Measuring Wetting Tension.**

Formamide, Volume Percent	Cellosolve _{TM} , Volume Percent	Wetting Tension _a dynes/cm
Formamide - Cellosolve_{TM} Mixtures		
0	100.00	30
2.5	97.5	31
10.5	89.5	32
19.0	81.0	33
26.5	73.5	34
35.0	65.0	35
42.5	57.5	36
48.5	51.5	37
59.0	41.0	39
63.5	36.5	40
67.5	32.5	41
71.5	28.5	42
74.7	25.3	43
78.0	22.0	44
80.3	19.7	45
83.0	17.0	46
87.0	13.0	48
90.7	9.3	50
93.7	6.3	52
96.5	3.5	54
99.0	1.0	56
Formamide - Distilled Water_b		
100.0	0	56
81.2	18.8	58
65.0	35.0	60
47.0	53.0	62
30.6	69.4	64
18.2	81.8	66
8.6	91.4	68
3.6	96.4	70

(a) Measured under conditions of $23 \pm 2^\circ \text{C}$ and $50 \pm 5\%$ relative humidity.

(b) Tentative mixtures, not yet included in ASTM procedure.

Table 2. Other Treat Level Measurements Used on Post-Treatment Surfaces.

Test Method	Procedure	Measurement
Water Spreading Test	A specified volume of distilled water is dropped on the material before and after corona treating.	The area covered by the water is measured and compared to determine the treat level.
Contact Angle Test	A drop of distilled water is placed on the web.	The relative contact angle between the droplet and the film surface is measured and compared.
Tilting Platform Test	A drop of distilled water is placed on the material which is secured in a horizontal plane. The plane is gradually tilted.	The angle at which the water begins to move down the plane is measured and compared.
Dye Stain Test	Material specimens are dipped into a special dye and dried in a vertical position.	The dye stains a treated surface but not an untreated surface.
Adhesion Ratio Test (based on ASTM tentative D-2141-63R)	Pressure-sensitive tape is applied with equal force to treated and untreated material.	The degree of force required to peel the tape from the material is measured and compared.
Ink Retension Test	Ink is spread on the surface of the material, allowed to dry, and covered with pressure-sensitive tape.	The relative area of ink that is lifted from the treated surface when the tape is removed is measured and compared.

Table 3. Typical Surface Tensions of Substrates.

Polymers	Surface tension in dynes per centimeter		
Hydrocarbons		Polytetrafluoroethylene (Teflon®)-PTFE	19-20
Polypropylene-		Polyvinylidene fluoride	25
PP, OPP, BOPP	29-31	Polyvinyl fluoride (Tedlar®)	28
Polyethylene-PE	30-31	Engineering thermoplastics	
Polystyrene PS	38	PET	41-44
Polystyrene (Low Ionomer)	33	Polycarbonate-PC	46
ABS	35-42	Polyimide	40
Polyamide	<36	Polyaramid	*
Polymethyl methacrylate-		Polyaryl ether ketone	<36
PMMA	<36	Polyacetal	<36
Polyvinyl acetate/ polyethylene copolymer-		Polyphenylene oxide-PPO	47
PVA/PE copolymer	33-44	PBT	32
Epoxy	<36	Polysulfone	41
Polyester	41-44	Polyethersulfone	50
Rigid Polyvinyl Chloride		Polyarylsulfone	41
PVC	39	Polyphenylene sulfide	38
Plasticized Polyvinyl Chloride-		Nylon	33-46
PVC	33-38	Elastomers	
Phenolic	*	Silicone	24
Fluorocarbons		Natural rubber	24
Chlorotrifluoroethylene--		Latex	*
CTFE (Aclar®)		Polyurethane	*
Polytetrafluoroethylene/ polyethylene copolymer-		Styrene butadiene rubber	48
PETFE	20-24	Fluoroelastomer	
Fluorinated ethylene propylene-FEP	18-22	Fluorocarbon copolymer elastomer	<36
		*Data not available at this time	

Table 4. Corona Treater Sizing Considerations.

To Be Treated	Examples	Comments
MATERIAL	Type, manufacturer, code number, etc.	<p>Sample testing has shown that the same type of material from different suppliers treats differently and holds treatment for different periods of time. The treatment variation can be as high as a factor of 4 between suppliers. Film should be tested prior to system sizing.</p> <p>For converting operations such as printing, laminating, coating, etc., pretreated film from the extruder is recommended. Untreated substrates may be difficult or impossible to treat in-line to levels conducive to good adhesion.</p>
WIDTH	Treatment width/roll face web width	<p>Stations can be designed to include wider roll faces than treatment width (electrode width) if untreated web edges are desirable. Determine if lane or skip treatment is required.</p>
THICKNESS	Film thickness	<p>Very thin webs may require provisions for light web tensions to reduce the possibility of static buildup or backside treatment.</p> <p>Heavy gauge films may require provisions for heavy tension, and both the minimum and maximum film width must be examined for roll deflection.</p> <p>The dielectric strength of a film which increases with the film thickness is also a sizing consideration for covered roll systems.</p>
LINE SPEED	Determine line speed.	<p>Line speeds that are 'typical,' 'anticipated,' or 'maximum' machine or line speed are not sufficient. For sizing, an accurate operational or web line speed is critical.</p>

Table 4. Corona Treater Sizing Considerations - continued

To Be Treated	Examples	Comments
ADDITIVES	Slip, antiblock, TiO ₂ , color, EVA, etc.	The type and amount of additives affect treating significantly. Be sure to indicate additives and the amount in ppm (parts per million). New films have witnessed levels of additives unheard of a few years ago. High slip can now mean anything from 800 ppm to 2100 ppm. The higher the slip content, the higher the power required to achieve the desired treatment level.
APPLICATION	Printing, laminating, extrusion coating, solvent/water-based printing, coating or laminating, extrusion, etc.	This information is required for proper sizing.
TREAT	One side or both.	The reason is obvious: two-side treatment requires twice the power of one side.
TREAT LEVEL	Dynes per centimeter.	Dynes are not linear or proportional to power settings. If the dyne level required is not known, sizing is based upon the application. Contact the coatings supplier for the dyne level required for the coating. Contact the treater manufacturer if questions arise.
LOCATION	Just prior to laminator after unwind, at top of tower, etc.	Please be exact regarding location. A system may be sized differently if it is located at the bottom of a blown film tower rather than the top where the film is still in a high energy state (warm) (warm). If the treater is mounted in-line, and some distance from the laminator, printer or coater etc., one or more of the following may occur:
		1. The treated surface can pick up contaminants through contact with an idler roll which affects the application.
		2. A high-slip film can lose treatment very fast. Therefore, a higher level of treatment may be required.
		3. Treatment on a slitter is common but can pose problems in blocking and treatment level decay.
		4. Review the proposed mounting location, the web path, the location of exhaust, and the high-voltage connections on the station.

Table 5. Problems with Corona Treatment Degradation.

Pinholes

If the base sheet contains a spot of high moisture or some other extra conductive material, the strong corona shorts through the spot and burns a small hole through the substrate.

Blocking

The molecular radicals formed by the corona have an attraction for the molecular layer on the other side of the web, and when the two sides come in contact, as in roll form, a self-adhering condition exists (6). It is not unknown for this attraction to be greater than the internal bond of the substrate and for actual substrate delamination to occur when the product is unrolled. The longer the roll is in storage and the tighter the wind, the more severe the problem. Blocking occurs more often near the core of the roll.

Scratches

Considerable heat is generated by the corona electrodes, which results in thermal expansion of the equipment. The air gap between the electrodes and the polyethylene surface is quite small and may only be adjusted for cross web uniformity while the system is shut down. During operation, the thermal expansion can warp the conventional metal electrode assembly enough to cause areas to actually touch the web, which results in a scratch. Increasing the overall gap to correct the problem may then result in areas of low treatment. Over the years, corona treater suppliers have done an excellent job of minimizing this thermal warping, but it remains a fact of life that the higher the treatment level attempted, the greater the heat generated and the greater the chance for thermal expansion on conventional metal electrodes. Also, the wider the unit, the greater the problem. On narrow-width units, as used on label printing presses, the problem is not as significant. Bare-roll treaters have eliminated the scratching problem.

Uneven Treatment Across the Web

Generally, the wider the sheet being treated, the greater the problem, and higher treatment levels only serve to magnify the problem. The most common manifestation of this problem is lower dyne levels on the edge of the sheet. This effect has been known to extend inward from as little as two inches to as much as a foot. When a multiroll setup is produced, i.e., the parent roll is slit into narrow rolls for the customer, rolls from the same production run have widely varying dyne results.

Backside Treating

Treatment of the material occurs when corona (ionized air) is present at the surface of the material. Thus, if the wrap is not sufficient on the treater roll (see Figure 35), or there are wrinkles in the material, backside treatment will occur. Solutions to backside treatment range from getting more wrap on the treater roll to installing nip rolls.

Heat-Sealing Problems

The true effect of high initial treatment on heat sealing is not documented, but preliminary indications are that it may interfere with the sealing properties of the product (20).

Downtime

The high power settings required to achieve the high treatment levels are not conducive to long life of the equipment. Various components of the electrical package such as transformers, diodes, rectifiers, etc., burn out prematurely. The mechanical portion also suffers shorter life, with electrode or covered roll burnout being a common problem. Again, bare-roll treaters have eliminated this problem.

Efficiency Loss

The problems created as a result of using high power levels thus cause downtime, lost production, and off-quality. These, in turn, increase the cost of manufacture, which must be absorbed by either the supplier or the end user.

Table 6. Loss of Corona Treatment Tests.

	Test	Loss
Initial sample just before contact	56	
After contacting untreated polyethylene surface on opposite side	39	17
After contacting corona treated polyethylene surface on opposite side	39	17
After contacting bare bleached base sheet on opposite side	43	13
After contacting flame primed bare base sheet on opposite side	39	17
After contacting slip sheeted bleached bond paper	44	12
After contacting slip sheeted bare aluminum foil	45	11
After contacting slip sheeted unbleached paper	49	7
Nontreated polyethylene surface	35	

Table 7. Effectiveness Levels of Corona Treatment Degradation.

Most Effective

A moderate treatment by the supplier at the time of manufacture followed by moderate treatment on the press just before ink laydown. This final treatment can be varied to optimize ink adhesion with heat-sealing characteristics.

Second Most Effective

Treatment on the press only. This can lead to difficulties if the polyethylene contains slip additives. In any case, it is much more effective than treating at the time of manufacture as the treated surface will not contact the other side before it contacts the printing station. Thus, the full results of the treatment still exist at the point of ink laydown.

Least Effective

Treatment by supplier only. The problems and difficulties encountered have been covered, but a quick summary follows:

1. Loss of a substantial portion of the treatment.
2. Production of pinholes, blocking, scratches, etc., caused by using extremely high power levels at the treater.

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